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FINAL REPORT
G.A.Skorobogatov
Contract No. F61708-96-W0229.
THEORETICAL AND EXPERIMENTAL ACHIEVEMENTS
IN THE FIELD OF INDUCED GAMMA EMISSION

G.A.Skorobogatov

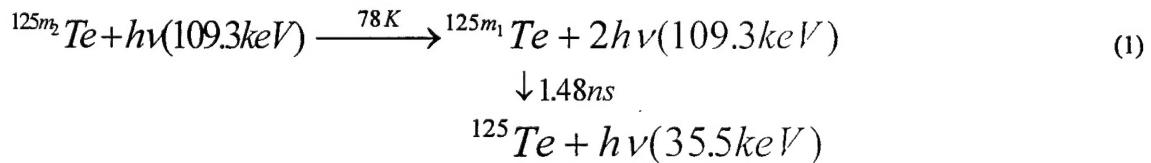
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Abstract

A critical analysis is presented for all published to date experimental data concerning the induced gamma-emission (*IGE*) in processes $^{125m_2}Te(\gamma, 2\gamma)^{125m_1}Te$, $^{123m^2}Te(\gamma, 2\gamma)^{123m^1}Te$, and $^{119m^2}Sn(\gamma, 2\gamma)^{119m^1}Sn$. The co-operative model of the *IGE* phenomenon is deduced from quantum electrodynamics.

Experimental results

In 1984 we published¹ a results of experimental study regarding the *IGE* process:



In Ref.¹ the experimental effect is taken as:

$$\varepsilon = \frac{\Delta\Phi}{\Phi}, \quad (2)$$

where $\Delta\Phi$ is the number of gamma-quanta emitted by stimulation at the $Be^{125m^2}Te$ sample temperature $T_{exp}=78K$, and Φ is the number of gamma-quanta spontaneously emitted at sample temperature 300K. The value $\varepsilon_{exp} = 1.2 \pm 0.6\%$ had been obtained in Ref. [1]. In order to exclude the contribution in ε_{exp} from a temperature rise of sample density we had reproduced the *IGE* process (1) in Ref.². In the latter work the experimental effect is taken as:

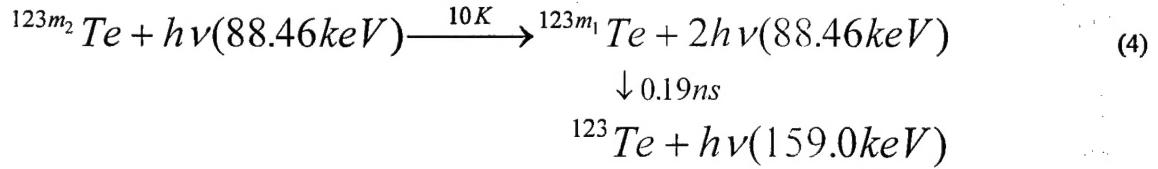
$$\varepsilon_{exp} = \frac{\Phi_{2\gamma}}{\Phi}, \quad (3)$$

where $\Phi_{2\gamma}$ is a number of coherent pairs $2h\nu$ (109.3 keV) originated in the process (1).

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Finally, in Ref.³ we had reproduced the *IGE* process (1) using both techniques (2) and (3) for ε_{exp} . The resulting experimental data are presented in Table 1.

Taken together References [1-3] demonstrate with confidence a reality of the *IGE* process (1). Nevertheless, by the early 1990s there was some uncertainty as to the mechanism of the *IGE* process. Hence, we undertook the experimental study regarding the *IGE* process³:



The obtained value of ε_{exp} for process (4) together with data for reaction (1) had demonstrated³⁻⁵ that realized *IGE* process is a collective polynuclear superradiance rather than stimulated emission of Mössbauer radiation. The corresponding theoretical equation for the effect value can be written as³⁻⁵:

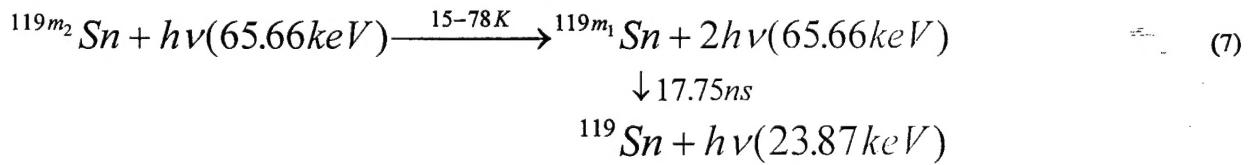
$$\mathcal{E}_{\text{theor}} = \frac{2\pi N_x f_m \beta \tau_{\text{down}}}{3\mu^3 (1+\alpha)(\tau_{\text{up}} + \tau_{\text{down}})}, \quad (5)$$

where N_x is a number of inversion, f_m is the Mössbauer factor, β is a branching factor, μ is the linear losses coefficient, α is an interval conversion factor, τ_{up} is the upper level life time, and τ_{down} is the lower level life time. Eqn. (5) holds⁵ only when the lattice temperature (T_{exp}) is decreased to the value T_Λ wherein a de Broglie thermal wavelength for nucleus $*X$ exceeds the gamma-quantum wavelength (Λ):

$$T_{\text{exp}} \leq T_\Lambda = \frac{(\hbar / \Lambda)^2}{2km_x}. \quad (6)$$

Here \hbar is the Planck constant, k is the Boltzmann constant, and m_x is a mass for the $*X$ nucleus. The relationship $N_x=[*X]$ was true in conditions of our experiments¹⁻⁵. One should recognize from the data of Table 1 that Eqn. (5) of co-operative model describes within the error limits all the experimental results obtained in Ref.¹⁻⁵.

In Table 1 we present also the results of experimental study of the process (4) in ref.⁶ and process



in Refs.^{6,7}.

Table 1. Comparison of theoretically calculated by formula (5) and experimentally measured ratio $\varepsilon = \Delta\Phi/\Phi_\gamma$, where $\Delta\Phi_\gamma$ is the number of gamma-quanta emitted by stimulation at matrix temperature T_{exp} , and Φ_γ is the number of gamma-quanta emitted spontaneously at matrix temperature 300K.

nuclide (*X)	$^{125m^2}Te$		$^{123m^2}Te$		$^{119m^2}Sn$	
polycrystal	<i>BeTe</i>		<i>Mg₃TeO₆</i>	<i>Mg₃TeO₆ + MgO</i>	<i>SnO</i>	<i>SnO₂</i>
T_A / K	10		6.6	6.6	3.6	3.6
Debye temperature / K	390		350	375	154	160
$[{}^*X] / 10^{18} \text{ atoms}\cdot\text{cm}^{-3}$	12±5	4.9±1.5	34±7	1.0±0.2	5±1	9±3
T_{exp} / K	78	10	10	78	15	78
Mössbauer factor $f_m(T_{\text{exp}})$	0.10±0.02	0.108	0.18±0.01	0.13	0.0214	0.01
μ_0^{-1} / cm	0.2062	0.2062	0.1639	0.33	0.0293	0.032
$(4\pi/3)[{}^*X]\mu_0^{-3} / 10^{16} \text{ atoms}$	44±18	18±6	63±13	16±5	0.053±0.011	0.12
$\frac{10^{20} f_m \tau_d}{2(1+\alpha_{up})(\tau_{up} + \tau_d)}$	4.03	4.35	0.148	0.103	0.0126	0.0059
$\varepsilon_{\text{theor}} / \%$	1.8±0.7	0.8±0.3	0.09±0.02	0.02±0.01	$7.8 \cdot 10^{-6}$	$7 \cdot 10^{-6}$
$\varepsilon_{\text{exp}} / \%$	1.2±0.6	0.35±0.15	0.05±0.03	0.30±0.06	≤0.0012	0.02±0.01
reference for ε_{exp}	Skor, Dz ¹ , 1984	Skor, Dz ³ , 1995	Skor, Dz ³ , 1995	Bond, Dz ⁶ , 1996	<i>ITEPh</i> ⁷ , 1989	Bond, Dz ⁶ 1996

Co-operative effects in stimulated emission

If we use a long-lived isomer both as storage and lasing level, the stimulated emission cross section is very small because of the very weak coupling between the gamma-radiation and the nuclei. Nevertheless, if the nuclei are imbedded in a lattice, co-operative effects in the stimulated emission could enhance the amplification and thus the gain substantially.

Consider an incoming gamma-radiation with a resonant (or near-resonant) frequency. That radiation interacts with all the nuclei in the ensemble and can stimulate those nuclei which are in the excited state to emit a photon. The probability for such a process can be written as⁸:

$$P_{stim.em.}(\hat{k}\sigma, t) = \left| \left\langle n_{\hat{k}\sigma} + 1, \Psi_F(\vec{r}_1, \vec{r}_2, \dots, \vec{r}_n, \vec{r}) \middle| \vec{J}(\vec{r}) \cdot \vec{A}_{\hat{k}\sigma}(\vec{r}, t) \middle| n_{\hat{k}\sigma}, \Psi_I(\vec{r}_1, \vec{r}_2, \dots, \vec{r}_n, \vec{r}) \right\rangle \right|^2, \quad (2-1)$$

where $\vec{A}_{\hat{k}\sigma}(\vec{r}, t)$ is the field at point \vec{r} associated to the stimulating radiation with momentum \hat{k} and helicity σ . For an incoming plane wave the vector potential is⁹:

$$\vec{A}_{\hat{k}\sigma}(\vec{r}, t) = \vec{A}_{\hat{k}\sigma}^* e^{-i(\hat{k}\vec{r} - \omega t)} + \vec{A}_{\hat{k}\sigma} e^{i(\hat{k}\vec{r} - \omega t)}, \quad (2-2)$$

in which $\vec{A}_{\hat{k}\sigma}^*$ and $\vec{A}_{\hat{k}\sigma}$ are respectively related to the photon creation operator $a_{\hat{k}\sigma}^+$ and the destruction operator $a_{\hat{k}\sigma}$. Since we consider only stimulated emission we can write:

$$\vec{A}_{\hat{k}\sigma}(\vec{r}, t) = a_{\hat{k}\sigma}^+ \vec{A}_{\hat{k}\sigma}(\vec{r}, t). \quad (2-3)$$

The total nuclear current operator $\vec{J}(\vec{r})$ can be written as a sum of currents $\vec{j}_l(\vec{r})$ each belonging to one single nucleus. The position vector \vec{r} can for each nucleus be written as a function of the position of the nuclear mass center \vec{r}_l and a charge distribution vector $\vec{\rho}_l$. Then:

$$\vec{J}(\vec{r}) = \sum_l \vec{j}_l(\vec{r}) = \sum_l \vec{j}_l(\vec{r}_l + \vec{\rho}_l). \quad (2-4)$$

The wave functions of the initial and final state are products of single nucleus wave functions:

$$\begin{aligned} \Psi_I(\vec{r}_1, \vec{r}_2, \dots, \vec{r}_n, \vec{r}) &= \prod_l \int_{|\Delta\vec{r}_l|} \phi_l(\vec{r}_l + \vec{\xi} + \vec{\rho}_l) f(\vec{\xi}) d\vec{\xi} = \\ &= \int_{|\Delta\vec{r}|} \prod_l \phi_l(\vec{r}_l + \vec{\xi} + \vec{\rho}_l) f(\vec{\xi}) d\vec{\xi}, \end{aligned} \quad (2-5)$$

$$\Psi_F(\vec{r}_1, \vec{r}_2, \dots, \vec{r}_n, \vec{r}) = \int_{|\Delta\vec{r}|} \prod_j \Phi_j(\vec{r}_j + \vec{\xi} + \vec{\rho}_j) f(\vec{\xi}) d\vec{\xi}. \quad (2-6)$$

Here the $f(\vec{\xi})$ function presents a Heisenberg uncertainty for the spatial coordinate \vec{r} .

As we consider only stimulated emission, we can restrict the initial state to all nuclei which are in the excited state. The total transition amplitude is then reduced to a sum of single nucleus matrix elements. Then, for every l in the absence of any temperature gradient in a lattice following relationship is true as result of the Heisenberg uncertainty relation:

$$|\Delta \vec{r}_l| = |\Delta \vec{r}| = \sqrt{\frac{2\pi\hbar^2}{m_X k T_{lat}}}, \quad (2-7)$$

where \hbar is the Planck constant, k is the Boltzmann constant, m_X is a mass of radiating nucleus. T_{lat} is a lattice temperature. Now instead equation (28) of Ref.⁸ we obtain following equation for total transition amplitude:

$$\mathbf{Z}_{tot}(\hat{k}\sigma, t) = \sum_l \int_{|\Delta\vec{r}|} \left\langle \Phi_l(\vec{r}_l + \vec{\xi} + \vec{\rho}_l) | \vec{j}_l(\vec{r}_l + \vec{\rho}_l) \vec{A}_{\hat{k}\sigma}(\vec{r}_l + \vec{\rho}_l) | \phi_l(\vec{r}_l + \vec{\xi} + \vec{\rho}_l) \right\rangle f(\vec{\xi}) d\vec{\xi}. \quad (2-8)$$

Under condition $f(\vec{\xi}) = \delta(\vec{\xi})$ our equations (2-5), (2-6), (2-8) coincides with equations (26), (27), (28) of Ref.⁸. Instead of equation (29) in Ref.⁸ the total transition amplitude becomes equal:

$$\begin{aligned} \mathbf{Z}_{tot}(\hat{k}\sigma, t) &= \int_{|\Delta\vec{r}|} \sum_l \left\langle \Phi(\vec{\rho} + \vec{\xi}) | \vec{j}(\vec{\rho}) \vec{A}_{\hat{k}\sigma}(\vec{r}_l + \vec{\rho}, t) T(-\vec{r}_l) | \phi(\vec{\rho} + \vec{\xi}) \right\rangle f(\vec{\xi}) d\vec{\xi} = \\ &= \sum_l \left\langle \Phi(\vec{\rho}) | \vec{j}(\vec{\rho}) \cdot \int_{|\Delta\vec{r}|} \vec{A}_{\hat{k}\sigma}(\vec{r} + \vec{\rho}, t) T(-\vec{r}_l - \vec{\xi}) f(\vec{\xi}) d\vec{\xi} | \phi(\vec{\rho}) \right\rangle, \end{aligned} \quad (2-9)$$

where:

$$\int_{|\Delta\vec{r}|} \vec{A}_{\hat{k}\sigma}(\vec{r}_l + \vec{\rho}, t) T(-\vec{r}_l - \vec{\xi}) f(\vec{\xi}) d\vec{\xi} = \vec{A}_{\hat{k}\sigma}(\vec{\rho}, t) \int_{|\Delta\vec{r}|} e^{-2ik(\vec{r}_l + \vec{\xi})} f(\vec{\xi}) d\vec{\xi}. \quad (2-10)$$

The total transition probability for stimulated emission can thus be written as:

$$P_{stim.em.}(\hat{k}\sigma, T_{lat}, t) = |...|^2 \sum_{j,l} \int_{|\Delta\vec{r}|} e^{-2ik(\vec{r}_l - \vec{r}_j + \vec{\xi})} f(\vec{\xi}) d\vec{\xi}, \quad (2-11)$$

where:

$$|...|^2 = \left| \left\langle \Phi(\vec{\rho}) | \vec{j}(\vec{\rho}) \cdot \vec{A}(\vec{\rho}, t) | \phi(\vec{\rho}) \right\rangle \right|^2 = \hbar \omega_{res} A_{21} \frac{f_m(T_{lat}) \beta \hbar \Gamma_{up} \hbar \Gamma_{tot}}{4(1+\alpha) \left[(E_{21} - \hbar \omega)^2 + \frac{1}{4} (\hbar \Gamma_{tot})^2 \right]}. \quad (2-12)$$

Here β is a branching factor, α is an interval conversion factor, f_m is the Mössbauer factor, Γ_{up} is a line width of the upper level, Γ_{tot} is the total line width, A_{21} is the Einstein coefficient, $\hbar \omega_{res} = E_{21}$ is the energy of electromagnetic transition.

Under condition $|\Delta\vec{r}| \ll |\vec{k}|^{-1}$ there are both situations outlined by equations (32)-(36) of Ref. [8]. However, under opposite condition $|\Delta\vec{r}| \geq |\vec{k}|^{-1}$ we get:

$$\sum_{j,l} \int_{|\Delta\vec{r}|} e^{-2ik(\vec{r}_l - \vec{r}_j + \vec{\xi})} f(\vec{\xi}) d\vec{\xi} = \kappa(T_{lat}) \sum_{j,l} 1 = (N')^2 \kappa(T_{lat}), \quad (2-13)$$

where:

$$N = [N]l_x l_y l_z \quad (2-14)$$

$$l_j = \text{Min}(L_j, \mu_j^{-1}), \quad (2-15)$$

$$\kappa(T_{lat}) = \begin{cases} 1, & \text{if } T_{lat} \leq T_\Lambda \\ (T_\Lambda / T_{lat})^{0.5}, & \text{if } T_{lat} > T_\Lambda, \end{cases} \quad (2-16)$$

$$T_\Lambda = \frac{(\hbar / \Lambda_{21})^2}{2km_X}, \quad (2-17)$$

L_j is the sample length along j -axis, μ_j is the absorption coefficient along j -axis, and Eqn. (2-17) is the same as Eqn. (6). Now one might see that equations (2-11) - (2-17) under condition $|\Delta\vec{r}| \geq |\vec{k}|^{-1}$ coincides completely with basic equation (5).

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A handwritten signature in black ink, appearing to read "G.A. Skorobogatov". The signature is fluid and cursive, with a large, stylized initial "G" and "A" followed by "Skorobogatov".